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博 士 学 位 论 文

浅海水声信道高效纠错编码技术研究

High-efficiency Error Correcting Code Techniques for Shallow Water Acoustic Channels

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摘 要

水声通信技术无论在军事还是民用领域均有重要应用价值。但由于水声信道，特别是浅海水声信道具有高噪、强多途及快速时变特性，从而使得实现能够可靠通信的系统极为困难。目前，无论采用相干，还是非相干调制方式的水声通信系统, 通常都需要进行信道编码才能获得满足工程应用需求的低误比特率。

论文在对海洋中声传播特性及浅海水声信道特性进行理论研究的基础上，建立了浅海水声信道多途传输模型；在对各种信道纠错编码进行分析讨论的基础上，深入探讨了两种趋近香农限的高效信道纠错编码，即 Turbo 码和 LDPC 码在浅海水声信道中的性能。

论文的主要工作如下：

1. 系统推导了基于最大后验概率的软判决译码、软输入软输出 Viterbi 译码等 Turbo 译码算法；分析了设计参数对 Turbo 码性能的影响；提出了一种抗水声多途干扰、带循环判决反馈均衡的 Turbo 译码结构。仿真表明，当误比特率为 10^{-5} 时，该结构比判决反馈均衡器与 Turbo 译码器直接级连的结构性能优 2dB 左右。
2. 研究了校验矩阵 H 的结构、数据帧长、码率等参数对 LDPC 码性能的影响; 研究了联合判决反馈均衡器时，规则 LDPC 码在浅海水声信道中的性能，将所得结果与 Turbo 码的结果进行比较可知, Turbo 码有编码简单、码率固定及在低 SNR 下性能优异等优点, 而规则 LDPC 码有不出现错误平层、准确的纠错结果、译码算法简单、时延小及码率可以任意设置等优点。
3. 将水声跳频技术与信道编码技术相结合，提出了一种基于 MFSK 调制、FFT 解调和 Turbo 编译码（或 LDPC 编译码）的高效水声跳频通信系统，仿真表明该系统即使在较低 SNR 下也可获得极低的误比特率。
4. 在上述理论及仿真研究基础上，以 TMS320 C6713 DSP 为核心构建了水声跳频通信系统实验样机。该样机提出了一种联合窄带滤波和线性调频信号互相关检测的快速水声帧同步方法，软件方法实现了信号的调制/解调、Turbo 及 LDPC 码的实时编译码。

5. 大量水池及海上现场水声数据传输实验证实了所设计样机的有效性、可靠性及稳健性。在厦门港浅海实验中，当传输距离 3km 时，样机获得了速率 250bits/s、0 误比特率的通信性能；当传输距离为 5km 时，样机获得了速率 250bits/s、10^{-5} 误比特率的通信性能。

本文创新之处在于：

1. 从理论上深入探讨了水声相干通信系统中 Turbo 码的性能，首次提出了一种抗多途干扰、带循环判决反馈均衡的 Turbo 译码结构；联合判决反馈均衡器，分析比较了 Turbo 码及 LDPC 码在浅海水声信道中的抗多途性能。
2. 首次以 TMS320 C6713 DSP 为核心构建了一套基于 MFSK 调制、FFT 解调和 Turbo 实时编译码（或 LDPC 实时编译码）的高效水声跳频通信系统实验样机；厦门港浅海水声数据传输实验证实了该样机的有效性、可靠性及稳健性。
3. 首次提出了一种联合窄带滤波和线性调频信号互相关检测的快速水声帧同步方法。

关键词：浅海水声信道；多途干扰；Turbo 码；LDPC 码；跳频通信

Abstract

Whether in military or civil use, underwater acoustic communication techniques have very important applications. It is very difficult to design an underwater acoustic communication system which can achieve reliable data transfer because the high noise, strong multipath and rapid time-varying exist in underwater acoustic channels, especially in shallow water acoustic channels. Now, whether in coherent or noncoherent underwater communication system, channel coding is often employed so as to achieve the bit error ratio which is low enough for satisfying the requirement of engineering application.

The propagation of sound in ocean and the features of shallow water acoustic channels are studied theoretically, based on which a multipath transfer model for the shallow water acoustic channels is presented. Furthermore, on the basis of analysing different kinds of error correcting code, the performance of two near Shannon limit high-efficiency error correcting code, namely Turbo and LDPC codes, is investigated in this dissertation.

The contents of the dissertation are as follows:

1. Some Turbo decoding algorithms, e.g., maximum a posteriori-based soft decision decoding and soft-input-soft-output Viterbi algorithm, are derived systemically. The influence of design parameters on the performance of Turbo code is analyzed. A new anti-multipath structure of Turbo decoder with iterative decision feedback equalizer (DFE) is built. Simulations show that the structure increase 2 dB in the performance compared with conventional Turbo decoder joint with DFE when bit error ratio is 10^{-5}.
2. The influences of the parameters such as the structure of the check-matrix *H*, length of the frame and code ratio on the performance of the LDPC code are analyzed. The performances of regular LDPC decoder joint with decision feedback equalizer in the underwater acoustic channels are investigated. The

result of LDPC decoder is compared with that of Turbo decoder, and it was found that the advantages of the Turbo decoder are that coding algorithm is simple, code ratio is fixed and the performance in low signal-to-noise ratio (SNR) is good, while the advantages of the LDPC decoder are that there is no error floor, correcting result is precise, decoding algorithm is simple, time-delay is short and code ratio is flexible.

3. A high-efficiency underwater acoustic frequency-hopping communication system is built by combining the underwater acoustic frequency-hopping and channel coding techniques. The MFSK modulation, FFT demodulation and Turbo coder/decoder (or LDPC coder/decoder) are employed in the above system. The simulation shows that the very low bit error ratio can be achieved even in low SNR environment.
4. Based on the above theories and simulations, an underwater acoustic communication experiment system is constructed by using TMS320 C6713 DSP as the core. The system introduces a new frame synchronization method by combining the techniques of narrowband filter and linear frequency modulation signal cross correlation detection. The modulation and demodulation of signals, and the real-time Turbo, LDPC coding and decoding are realized by the software method.
5. The validity, reliability and stabilization of the experiment system are proved by many underwater acoustic data transmission experiments which are carried out in a pool and in Xiamen harbor. The communication performances of the system achieved in the shallow water acoustic channels of Xiamen harbor are that the data rate is 250bits/s, the bit error ratio is 0 and the frame error ratio is 0 when communication distance is 3km, while the data rates is 250bits/s, the bits error ratio is 10^{-5} and the frame error is 10^{-3} when the communication distance is 5km.

The innovations of the dissertation are as follow:

1. The performance of Turbo code in high speed underwater acoustic coherent communication systems is studied theoretically, based on which a new anti-multipath structure of Turbo decoder with iterative decision feedback

equalizer is introduced first time. The performance of the Turbo code in shallow water acoustic channels is compared with that of LDPC code when the decision feedback equalizer is employed simultaneously.

2. A high-efficiency underwater acoustic frequency-hopping communication system is introduced. The MFSK modulation, FFT demodulation and Turbo coder/decoder (or LDPC coder/decoder) are employed in the system. Furthermore, an experiment system is constructed by using TMS320 C6713 DSP as the core. The experiments done in Xiamen harbor have proved the validity, reliability and stabilization of the system.
3. A new underwater acoustic frame synchronization method by combining the techniques of narrowband filter and linear frequency modulation signal cross correlation detection is introduced first time.

Key words: Shallow water acoustic channels; multipath interference; Turbo code; LDPC code; Frequency hopping communication

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